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Combustion, emission and engine performance characteristics of used cooking oil biodiesel—A review

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ABSTRACT

As the environment degrades at an alarming rate, there have been steady calls by most governments following international energy policies for the use of biofuels. One of the biofuels whose use is rapidly expanding is biodiesel. One of the economical sources for biodiesel production which doubles in the reduction of liquid waste and the subsequent burden of sewage treatment is used cooking oil (UCO). However, the products formed during frying, such as free fatty acid and some polymerized triglycerides, can affect the transesterification reaction and the biodiesel properties. This paper attempts to collect and analyze published works mainly in scientific journals about the engine performance, combustion and emissions characteristics of UCO biodiesel on diesel engine. Overall, the engine performance of the UCO biodiesel and its blends was only marginally poorer compared to diesel. From the standpoint of emissions, NO*x* emissions were slightly higher while un-burnt hydrocarbon (UBHC) emissions were lower for UCO biodiesel when compares to diesel fuel. There were no noticeable differences between UCO biodiesel and fresh oil biodiesel as their engine performances, combustion and emissions characteristics bear a close resemblance. This is probably more closely related to the oxygenated nature of biodiesel which is almost constant for every biodiesel (biodiesel has some level of oxygen bound to its chemical structure) and also to its higher viscosity and lower calorific value, which have a major bearing on spray formation and initial combustion.

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1. Introduction

In recent years, increased environmental concerns, depletion of petroleum resources, and several other socioeconomic aspects have driven research to develop alternative fuels from renewable resources that are cheaper and environmentally acceptable. Many researchers have tried to develop vegetable oil-based derivatives that approximate the properties and performance of petroleum-based diesel fuel. Esters of fatty acids (biodiesel), derived from the transesterification of vegetable oils have properties similar to petroleum-based diesel fuel.

Literature is replete with advantages derived using biodiesel: it helps to reduce the carbon dioxide emission to the atmosphere, it is renewable in nature and safer to handle, it has no aromatic compounds, practically no sulphur content, and oxygen atoms in the molecule of fuel may reduce the emissions of carbon monoxide (CO), total hydrocarbon (THC) and particulate matter (PM) [1–7]. However, biodiesel is known to have some drawbacks when compared with petroleum-based diesel fuel such as worse low-temperature properties, greater emissions of some oxygenated hydrocarbons, higher specific fuel consumption, decrease in brake thermal efficiency and higher production cost [8–14]. The problem of production cost has been partially solved by the use of waste cooking or animal fats as the raw materials in the transesterification process [15]. However, during frying, vegetable oil undergoes various physical and chemical changes, and many undesirable compounds are formed. These include free fatty acid and some polymerized triglycerides which increase the molecular mass and reduce the volatility of the oil. Therefore, fatty acid esters obtained from frying oil influences the fuel characteristics (such as the viscosity and it is believed that the burning characteristics reduce) leading to a greater amount of Conradson carbon residue [16]. Comprehensive reviews on biodiesel production from used cooking oil (UCO) can be found in [16,17].

Since diesel engines are not specifically manufactured for biodiesel fuel use, then the study of biodiesel from waste cooking oil is not complete unless it is tested in a diesel engine. Many studies have been conducted to compare the performance of biodiesel obtained from waste cooking oil with that of petroleum-based diesel fuel. Hence, the main objective of this paper is to analyze by means of literature review the engine performance, combustion and emission characteristics of diesel engines fuelled with biodiesel produced from waste cooking oil and/or its blends with petroleum-based diesel fuel. Table 1 [21] shows a comparison of fuel properties for a WCO biodiesel, fresh oil biodiesel and diesel.

Table 1
Test fuel properties.

Characteristics	Fresh oil biodiesel	Esters of WCO [WCO biodiesel]	Diesel
Density at 40 °C (kg/m^3)	870.6	876.08	807.3
Specific gravity at 15.5 °C	0.887	0.893	0.825
Distillation temperatures			
10% recovery temperature	324	340	165
50% recovery temperature	336	345	265
90% recovery temperature	312	320	346
Flash point (°C)	159	160	53
Fire point (°C)	165	164	58
Kinematic Viscosity at 40 °C (mm^2/s)	2.701	3.658	1.81
Calorific value (kJ/kg)	40120.78	39767.23	42347.94
A.P.I. gravity	27.83	26.87	39.51
Cetane index	50.025	50.54	56.21
Aniline point (°C)	NA	NA	77.5

"NA" stands for not available.

2. Combustion characteristics

Dorado et al. [18] used a DI diesel Perkins engine to study the effect of used olive oil methyl ester on combustion efficiency. Results obtained showed that as oxygen concentration increased, it provided more oxygen for combustion. The combustion efficiency did not drop during testing and remained almost constant using either waste olive oil methyl ester or diesel fuel.

The combustion performance of ethyl ester of used palm oil relative to baseline diesel fuel in a water-cooled furnace was investigated by Tashtoush et al. [19]. The combustion efficiency was tested over a wide range of air/fuel ratio ranging from very lean to very rich (10:1–20:1). The findings showed that at a lower energy rate, biodiesel burned more efficiently with higher combustion efficiency (66%) compared to 56% for the diesel fuel. At higher energy input, the biodiesel combustion performance deteriorated, because of its high viscosity, density and low volatility.

Ozkan et al. [20] made a comparison of the effective pressure of used cooking oil biodiesel, used cooking oil biodiesel blended with glycerine and petroleum-based diesel in a direct injection compression ignition engine. The results obtained showed that the effective pressure of these fuels yielded similar results for values up to 2000 rpm.

Sudhir et al. [21] conducted test on a single-cylinder, four-stroke, naturally aspirated, open chamber (direct injection) water-cooled, 5.2 kW computerized diesel engine test rig using palm oil based waste cooking oil (WCO) and biodiesel from fresh palm oil. The purpose of this paper was to analyze the potential of waste cooking oil (WCO) for their suitability as feed stock for biodiesel preparation and to compare the fuel properties of the derived esters of WCO (WCO biodiesel) with those esters of fresh oil and baseline diesel fuel. Results showed that though the combustion temperature and pressure was low for biodiesel operation, the NO*x* emission was almost the same as that of diesel operation. Also, CO, CO_2 and O_2 emissions were approximately same as that of baseline diesel emission. However, un-burnt hydrocarbon (UBHC) emissions of waste cooking oil biodiesel fuel were lower than baseline diesel operation. Also, the UCO biodiesel had very low level of sulphur content; hence sulphate emissions were virtually eliminated.

The effect of alcohol type used in the production of waste cooking oil biodiesel on diesel engine performance and emissions was examined by Lapuerta et al. [22] using a four-cylinder, four-stroke, turbocharged, intercooled, direct injection 2.2 l Nissan engine. The calculation of the heat release fraction from the in-cylinder pressure signal through a diagnostic model showed no differences in combustion timing. However, a very slight difference in the premixed peak of the rate of heat release of the two biodiesel fuels tested (Waste Cooking Oil Methyl Ester and Waste Cooking Oil Ethyl Ester), their blends with diesel fuel and diesel fuels was observed. This difference was due to pre-combustion caused by the pilot injection. Although the cetane numbers of the fuels tested were not measured, the heat release and rate of heat release diagrams showed similar auto-ignition behavior in all cases.

A detailed study on the effects of the percentage of used cooking oil methyl ester (UCOME) on combustion characteristics (ignition delay, rate of pressure rise, peak pressure, heat release) has been undertaken by Rao et al. [23]. It was observed that the ignition delay periods of UCOME and its blends are significantly lower than that of diesel and decrease with increase in the percentage of UCOME. Also, for all test fuels exhibit a general trend of decrease in ignition delay with increase in load. The chart of variation of peak pressures with brake power for UCOME-diesel blends and diesel shows that the peak pressure is slightly higher for UCOME-diesel blends compared to diesel. This shows that the peak pressure is not very much affected using UCOME and its blends compared to diesel. With all tests performed at an ignition timing of 23.4° bTDC,

the rate of pressure rise for diesel was higher compared to those of UCOME and its blends. Also, the maximum rate of pressure rise decreases with increase in UCOME in the blend. When the heat release of UCOME and its blends were compared with that of diesel, the maximum heat release rate of 71.459 J/°CA was recorded for diesel at 6° bTDC, while UCOME records 51.481 J/°CA at 8° bTDC. The results show that the maximum heat release rate decreases with increase in percentage of UCOME in the blend. It can also be observed that maximum heat release rate occurs earlier with the increase in the percentage of UCOME in the blend.

2.1. Analysis of the trend of combustion characteristics

2.1.1. Ignition delay

In the combustion analysis great attention is paid to the ignition delay as noise, vibrations, mechanical stress and polluting emissions largely depend on this parameter and time delay. Ignition delay is defined as the time interval during which each droplet transforms for combustion. Time delay determines the quantity of premixed flame formed the rate of pressure increase and its maximum value.

A possible explanation for lower ignition delay periods of UCOME and it blends with increase in the percentage of UCOME might be due to higher cetane number of UCOME and its blends compared to diesel. Another possible explanation may be the presence of oxygen present in UCOME and the splitting of higher molecules of UCOME such as oleic and linoleic fatty acid methyl esters into lower molecules of volatile compounds during injection which advances the start of combustion causing earlier ignition. The reduction in ignition delay with increase in load might be as a result of higher combustion chamber wall temperature at the time of injection and reduced exhaust gas dilution.

2.1.2. Peak pressure

The higher peak pressure of UCOME-diesel blends compared with diesel may be due to lower ignition delay for UCOME and its blends. The reduction in ignition delay with increase in percentage of UCOME which results in earlier combustion might lead to the slightly higher peak pressures. Another possible explanation of this may be the higher oxygen content of UCOME which favors better combustion. Also since UCOME has lower calorific value, a large of amount of fuel needs to be burned in premixed combustion stage and this may result in slightly higher peak pressure.

2.1.3. Rate of pressure rise

The trend obtained for the rate of pressure rise may be a consequence of the decrease in ignition delay with increase in percentage of UCOME in the blend. The reduced ignition delay implies that the quantity of accumulated fuel during ignition delay is lesser than during higher ignition delay. Hence the pressure rise is not as drastic as in the case of diesel. Also the premixed combustion heat release is higher for diesel which may be responsible for higher rate of pressure rise.

2.1.4. Rate of heat release

The observations made for the rate of heat release may also be attributed to the reduction in ignition delay of UCOME and its diesel blends and can be explained in a similar manner as the rate of pressure rise. Also, lower calorific value of UCOME and its blends may contribute to lower heat release [24]. It is also possible that an increase in the oxygen fraction of the injected fuel provides an increase in the maximum heat release rate and in the fraction of fuel burned in the premixed combustion phase; this case is more obvious at a high engine speed.

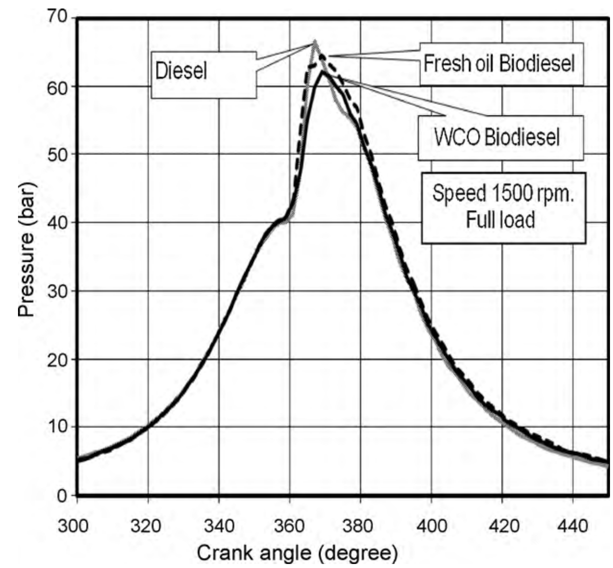


Fig. 1. Pressure versus crank angle diagram for the three test fuels.

2.1.5. Pressure variation with crank angle

The pressure variation in the cycle is important in the analysis of the performance characteristics of any fuel. WCO biodiesel, fresh oil biodiesel and diesel follow similar pattern of pressure rise. However, there are distinct differences between biodiesel and its blends compared with diesel. Viscosity of WCO biodiesel is higher than that of diesel. Because of its higher viscosity spray characteristics are greatly affected as high viscous nature of fuel minimizes the fineness of atomization. On the other hand, the cetane index of the WCO biodiesel is lower than that of diesel. Hence both factors might probably combine to increase the physical delay period, which results in poor engine performance. The increase in delay period results in poor combustion and causes low peak pressure as depicted in Fig. 1 [21].

3. Emission characteristics

Mittelbach et al. [25] tested methyl esters prepared using waste cooking oil for their emissions in a vehicle with an inertia weight of 1360 kg powered by a 2.3-L turbocharged, four-cylinder, four-stroke, direct injection diesel engine with exhaust gas recirculation (EGR). The test was carried under transient operating conditions on a chassis dynamometer under the US Federal Test Procedure (US-FTP) and in the Highway Fuel Economy Test (HWFET). Test results were compared with US-2D reference fuel. The ester fuel showed slightly lower hydrocarbon (HC), and CO emissions but increased NO*x*, compared to US-2D fuel, under US-FTP and almost doubled the NO*x* values under HWFET test. Particulate matter (PM) emissions were reduced significantly under both test conditions when ester fuel was used. The polycyclic aromatic hydrocarbon (PAH) emissions of the ester fuel were higher than those of the US-2D fuel, but the differences were within tolerance limits. The ester fuel was also tested in a Volkswagen Rabbit automobile powered by a 1.6-L four-cylinder, four-stroke diesel engine with indirect injection. A mixture of the ester fuel with diesel fuel in the ratio of 1:1 was chosen, and a total of 100 L of ester fuel was consumed. Results showed that the smoke emissions were extremely low, and only a faint smell of burnt fat was detected.

Biodiesel blends of methyl esters from waste cooking oil (0%, 10%, and 15%) with diesel fuel have been tested in various diesel engines by Leung [26]. The first test was carried out on a Cummine LT10 engine test bed and a 7% reduction in smoke opacity at a blending ratio of 15% was observed. The second test was conducted

on an Isuzu 5-tonne lorry with a biodiesel blending ratio of 10%. The results showed a reduction of air pollutants from 1.5% to 44% for CO and HC except NO*x* which has a slight reduction at idle condition but increased by about 16% at 2500 rpm. The third test was conducted on a diesel generator (Robin GS 3300RD), which consists of a generator and a four-stroke single-cylinder diesel engine. Results show that at idling stage, increasing biodiesel content slightly reduced NO*x* levels while the NO*x* level slightly increased or decreased under loaded condition. Also the CO level decreased with increasing biodiesel percentage for both idle and loaded conditions. It is noted that under loaded conditions, the CO level was less than that at idling, indicating that better combustion occurred resulting in a higher level of NO*x*.

Hamasaki et al. [27] tested their single-cylinder engine at 2000 rpm and different loads with diesel fuel and three biodiesel fuels from used cooking oil. The acid values of the biodiesel were different; from 0.33 to 0.90 mg KOH/g. CO emissions were increased as the acid value was increased. They measured slight decreases in NO*x* emissions at low loads but increases at high loads. On the other hand, larger decreases in particulate matter emissions were observed at high load operation conditions. The study also revealed reductions from smoke opacity measurements.

Guo et al. [28] produced biodiesel from recycled oils and tested it in a 1998 Ford light goods van with a four-stroke four-cylinder, water-cooled diesel engine using a chassis dynamometer model ECCT 500108. Two loadings (12 and 29 kW) were applied onto the vehicle and constant speed was maintained during the emission testing. Results showed that all the measured smoke levels decreased with increasing biodiesel blending percentage. A maximum reduction of 83% in a smoke opacity was recorded for 100% biodiesel usage. It was also observed that the HC concentrations at all biodiesel blending percentages were less than the neat petroleum diesel. The CO concentration exhibited similar trend as the HC curves except that the changes were not so dramatic. Also the NO*x* concentration only varied slightly for the two loadings at the full range of biodiesel tested.

In comparing engine performance and emissions for petroleum diesel fuel, yellow grease biodiesel and soybean oil biodiesel, Canakci and Van Gerpen [29] obtained 65% reductions in particulate matter emissions with both soybean oil and waste oil biodiesel fuels as well as for diesel fuel.

Investigation of oxides of nitrogen emissions from biodiesel-fueled engines using different alkyl esters of vegetable oil and animal fats including methyl yellow grease showed that with biodiesel fuels, NO*x* emissions were usually higher than those from diesel fuel [30].

Ethyl ester obtained from used palm oil was tested in a single-cylinder direct injection engine by blending different portions of ester with diesel fuel [31]. The blends included 100% ester (100O); 75:25 ester/diesel (25D), 50:50 ester/diesel (50D), 25:57 ester/diesel (75D), and 100% diesel fuel (100D). All of the blends, including 100% ester, were tested in the same engine, and their performance was compared with diesel fuel. The emissions of CO, unburned hydrocarbons (UBHC), CO_2, oxygen and smoke were examined. Overall, the 50:50 blends consistently gave the minimum amounts of all emissions considered. This blend was the leanest (highest oxygen availability) to burn. Generally, it was observed that the blends were superior to the baseline fuel (100D) as far as CO and UBHC are concerned. NO*x* are of prime importance to engine exhaust. However, the NO*x* data gathered in this work were deemed unreliable by the authors and were dropped from the analysis.

The exhaust emissions of a diesel engine direct injection Perkins engine fueled with waste olive oil methyl ester were studied at several steady-state operating conditions by Dorado et al. [18]. Emissions were characterized with neat biodiesel from used olive oil and conventional diesel fuel. Results revealed that the use of biodiesel resulted in lower emissions of CO (up to 58.9%), CO_2 (up to 8.6%), NO (up to 37.5%), and SO_2 (up to 57.7%), with increase in emissions of NO_2 (up to 81%).

Ulusoy and Tekin [32] investigated the effects of biodiesel made from used frying oil on emissions in a Fiat Doblo 1.9 DS, four-cylinder, four-stroke, and 46 kW power capacity diesel engine. Comparative measurements with No. 2 diesel fuel were conducted on emission characteristics of each of the fuel used. According to emission tests, as a result of biodiesel consumption, a reduction of 8.59% in CO emission while an increase of 2.62% and 5.03% were observed in CO_2 emission and NO*x* emission, respectively. On the other hand, HC emissions and PM emissions decreased by 30.66% and 63.33%, respectively. It was concluded that these engine emission tests show that biodiesel is a more environment friendly fuel than No. 2 diesel fuel.

Exhaust emission characteristics were evaluated in a Toyota van, powered by a 2-L indirect injection (IDI) naturally aspirated diesel engine, operating on a vegetable-based waste cooking oil methyl ester by Gonzalez-Gomez et al. [33]. Tests were conducted on a chassis dynamometer and the data were compared with previous results conducted on the same vehicle using mineral diesel fuel. The data obtained included smoke opacity, CO, CO_2, O_2, NO, NO_2 and SO_2.These data showed that waste cooking oil methyl ester developed a significant lower smoke opacity level and reduced CO, CO_2, SO_2 emissions. However, NO_2, NO, and O_2 levels were higher with the waste vegetable oil based fuel.

The engine and road performance tests of biodiesel fuel derived from used cooking oil were evaluated in a Renault Mégane automobile and 75 kW Renault Mégane diesel engine in winter conditions for 7500-km road rests, and the results were compared with those using No. 2 diesel fuel [34]. Results showed that the engine exhaust gas temperatures, at each engine speed for biodiesel were less than those of No. 2 diesel fuel. The difference appears to be minimal at 2000 rpm engine speed.

The emission characteristics of biodiesel fuel produced from hazelnut soapstock/waste sunflower oil mixture and its blend with No. 2 diesel fuel was investigated by Usta et al. [35]. The study showed that at full load, the CO emissions of the blend were higher at low speed and lower at high speeds than those of diesel fuel, while the blend resulted in higher CO_2 emissions in the experimental range. At partial loads, it was found that the blend did not cause significant changes in the CO and CO_2 emissions. There was a significant SO_2 reduction with the blends due to lower sulphur content of the biodiesel. NO*x* emissions slightly increased due to the higher combustion temperature and the presence of fuel oxygen with the blend at full load. However, the increasing amount of NO*x* emission slowed down with decreasing load.

Generators are crucial equipment of industry and because of their indoor applications, the emission characteristics is important. Cetinkaya and Karaosmanoğlu [36] conducted emission tests on electric generators using biodiesel prepared from waste cooking oil. The tests were conducted on a 90-mm-stroke, one-cylinder, and 9-kW 3LD510 coded diesel engine. Consecutive tests on No. 2 diesel fuel, B100 and B20 were conducted, and the results compared with each other. Compared to No. 2 diesel fuel, B100 and B20 blends showed improved results, in regard to emissions. The use of B100 resulted in lower smoke production than that of B20.

Armas et al. [37] carried out several load, speed and start-up transient tests in a direct injection engine with two biodiesel fuels from waste oil and sunflower oil, pure and differently blended with a diesel fuel. Except for the start-up test, all the transient tests showed noticeable decreases in smoke opacity when biodiesel content was increased.

The trace formation from the exhaust tail gas of a diesel engine when operated using neat biodiesel from WCO, WCO biodiesel/blends, and mineral diesel fuels has been studied by Lin et al. [38].

The experiments were performed on a four-cylinder, four-stroke 2200 cc pre-combustion diesel engine. The emission tests were carried out at engine speeds ranging from 1000 to 2000 rpm at 200 rpm increment. The results showed that B20 produced the lowest CO concentration for all engine speeds. B50 produced higher CO_2 than other fuels for all engine speeds, except at 2000 rpm where B20 gave the highest. The biodiesel and biodiesel/diesel blend fuels produced higher NO*x* for various engine speeds. SO_2 formation not only showed an increasing trend with increased engine speed but also showed an increasing trend as the percentage of diesel increased in the fuels. Among the collected data, the PM concentrations from B100 engines were higher than from other fuelled engines for the tested engine speed and most-contained fuels produced higher PM than the pure diesel fuel did. The species of trace formation in the biodiesel-contained fuelled engine exhaust were mainly C_nH_{2n+2}, diethyl phthalate (DEP), and diphenyl sulphone (DPS). For the B100, B80, B50, and D fuelled engines; $C_{15}H_{32}$ was the dominant species for all engine speeds, while squalene ($C_{30}H_{50}$) was dominant for B20. DEP was only observed in the B100, B80, and B50 fuelled engines. The D fuelled engine showed a higher DPS production for engine speeds higher than 1200 rpm.

Utlu and Koçak [39] investigated the effect of biodiesel fuel obtained from waste frying oil (WFO) on direct injection diesel engine performance and exhaust emissions. The study focused on variations of smoke density, CO emission, CO_2 emission, exhaust temperature and NO*x* changes measured between 1750 and 4500 rpm. Results showed that while smoke intensity decreased in average of 22.46% for waste frying oil methyl ester (WFOME) compared to diesel fuel, the emission values for CO and NO*x* decreased by 17.14% and 1.45%, respectively. Also, exhaust temperature and CO_2 emission of WFOME decreased on average 6.5% and 8.05%, respectively than diesel fuel.

The impact of WCO biodiesel/diesel blend fuels on an YC6M220G turbocharge diesel engine exhaust emissions has been evaluated and compared with diesel fuel by Meng et al. [40]. The emissions of CO, UBHC and nitrogen oxide were examined for all the test fuels (B20, B50, 20% refined biodiesel blend B'20 and the reference fuel B0). Results showed that B20 and B50 blend fuels both were inferior to the reference fuel as far as CO and UBHC were concerned and better in nitrogen oxide emission. However, B'20 consistently gave the minimum amounts of all emissions considered. CO and HC were reduced by 18.6% and 26.7%, respectively. The total particles emission for B'20 was 0.0714 g/(kW h) and was reduced by 20.58% compared to the reference fuel B0 which had 0.0899 g/(kW h) total particles emission.

Experimental results have been obtained by testing two different alcohol-derived biodiesel fuels: methyl ester and ethyl ester, both obtained from waste cooking oil [22]. These biodiesel fuels were tested pure and blended (B30 and B70) with a diesel reference fuel, which was tested too, in a 2.2-L, common-rail injection diesel engine. Results showed that pure biodiesel fuels, compared to reference fuel, gave very slight differences in NO*x* emissions, and sharp reductions in total HC emissions, smoke opacity and particle emissions, despite the increasing volatile organic fraction of the PM. The type of alcohol used in the production process was found to have a significant effect on the total HC emissions and on the PM composition. As the alcohol used was more volatile, both the HC emissions and volatile organic fraction of the particulate matter were observed to increase. Ethyl esters showed lower THC emissions than methyl esters in medium load conditions, and no clear trend in low load condition. Also, if the effect of the alcohol used is analyzed, slightly higher reductions (with respect to the reference fuel) in both opacity and PM emissions were observed in the case of methyl ester.

Rao et al. [23] compared the emissions of pollutants: nitrogen oxides, CO, UBHC emissions and smoke of UCOME and its blends with diesel. Results showed that while there was a gradual increase in NO*x* emissions with increase in percentage of UCOME in the fuel, the CO emissions, UBHC and smoke intensity decreased as the percentage of UCOME in the blend increases. The exhaust gas temperature was observed to have increased with load. It was also observed that the exhaust gas temperature increases with percentage of UCOME in the test fuel for all the loads.

Lapuerta et al. [41] conducted a study on the diesel particulate emissions from used cooking oil biodiesel on a four-cylinder, four-stroke, turbocharged, intercooled, direct injection diesel engine. Two different biodiesel fuels were tested either in pure or as B30 and B70 blends with a reference diesel fuel. The main objective of the work was to study the effect of biodiesel blends on particulate emissions, measured in terms of mass, smoke opacity and size distributions. The results showed a sharp decrease in both smoke and PM emissions as the biodiesel concentration was increased. The mean particle size also reduced with biodiesel concentration, but no significant increases were found in the range of the smallest particles. No important differences were found between the two tested biodiesel fuels.

Emissions tests on microwave-assisted continuous biodiesel produced from waste frying palm oil have been studied and compared with No. 2 diesel fuel by Lertsathapornsuk et al. [42]. Results indicated that WFPOEE and its B50 blend showed cleaner exhaust emissions as HC and CO were decreased by $25.11 \pm 0.03\%$ and $17.96 \pm 0.12\%$, respectively. However, NO*x* emission tended to increase at higher loads with B100 emitting higher levels of NO*x* than the No. 2 diesel fuel.

Similarly, Reefat et al. [43] used a Perkins four-cylinder, four-stroke diesel engine to investigate the exhaust emissions of WCO biodiesel produced by microwave irradiation. Evaluation of the data indicate that, despite the small increase in NO*x* emissions, decreases in CO, NO and NO_2 emissions as a result of firing biodiesel were found to be statistically important compared to the emissions when burning diesel.

Roskilly et al. [44] tested diesel fuel and biodiesel from recycled cooking fat and vegetable oil in a small marine craft diesel engine. The tests were performed on Perkins 404C-22 and Nanni diesel 3.100HE engines. The tests found NO*x* emissions reduced with biodiesel and CO emissions lower when the engines operated at higher loads using biodiesel. For Perkins engine, the differences in exhaust temperatures between fossil diesel and biodiesel were less than 2% while for Nanni engine, the exhaust temperatures were a little higher (1.8–11.5%) for biodiesel as compared to fossil diesel.

In a study by Ozsezen et al. [45] biodiesel from used frying palm oil and its blends with diesel fuel were used in a four-cylinder, naturally aspirated indirect injection (IDI) diesel engine. Using petroleum-based diesel fuel (PBDF), biodiesel, and its blends, the engine performance, injection, and combustion characteristics were investigated over a range of engine speeds at full load.

The diesel engine exhaust emission analysis using waste cooking oil biodiesel fuel with an artificial neural network (ANN) has been studied by Ghobadian et al. [46]. To acquire data for training and testing the proposed ANN, two cylinders, four-stroke diesel engine fuelled with WVO-biodiesel and diesel fuel blends were operated at different engine speeds. The experimental results revealed that blends of WVO methyl ester with diesel fuel provide improved emission characteristics. Using some of the experimental data for training, an ANN model was developed based on standard Back-Propagation algorithm for the engine. Results showed that the ANN model can predict the exhaust emissions quite well with correlation coefficient (R) 0.929 and 0.999 for CO and HC emissions, respectively.

Similarly, Canakci et al. [47] used neural networks to predict the performance and exhaust emissions of a diesel engine fueled with biodiesel produced from waste frying palm oil. Results showed

that CO emissions decreased with increase in biodiesel content in the fuel blend with pure biodiesel producing the lowest CO emissions for all engine speeds compared to diesel fuel. For the biodiesel blends, the UBHC amount in the exhaust decreased with increase in the amount of biodiesel in the fuel blend. Smoke opacity decreased with increasing amount of biodiesel in the fuel blend, especially at high engine speeds while NO*x* emissions increased with increasing fraction of biodiesel in the fuel blend.

A study on emission performance of a diesel engine fuelled with five typical methyl ester biodiesels has been carried out by Wu et al. [48]. The five methyl esters included waste cooking oil methyl ester (WCOME), cottonseed methyl ester (CME), soybean methyl ester (SME), rapeseed methyl ester (RME) and palm oil methyl ester (PME). Total PM, dry soot (DS), non-soot fraction (NSF), NO*x*, UBHC and CO were investigated on a Cummins ISBe6 Euro III diesel engine and compared with a baseline diesel fuel. Results revealed the following: the biodiesel that reduced PM the most, in descending order are: WCOME, PME, CME, RME, and SME; biodiesels that reduced DS the most, in descending order, are: PME, WCOME, CME, RME, and SME; SME and RME resulted in an increase in NSF of 45% and 11% relative to diesel fuel, NSF of PME was close to diesel fuel while CME and WCOME resulted in an NSF decrease of 8% and 21% relative to diesel fuel; the biodiesels that resulted in the least NO*x*, in descending order, are: CME, PME, SME, WCOME, and RME while the reduction in HC in descending order was: PME, WCOME, RME, CME, and SME.

3.1. Analysis of the emission characteristics

3.1.1. Exhaust gas temperature

The exhaust gas temperature indicates the effective use of the heat energy of a fuel. The heat loss in the exhaust pipe or an increase in the exhaust temperature reduces the conversion of heat energy of the fuel to work. There have been a wide range of reports on exhaust gas temperature for UCOME and its blends. A lower value of exhaust gas has been observed at each engine speed for UCOME biodiesel compared to diesel. The low value of engine exhaust gas temperature indicates that the used cooking oil originated biodiesel burned well in the cylinders when compared to No. 2 diesel fuel. This result is relevant when the higher O_2 content of the used cooking oil is considered [34]. The lower value of exhaust temperature may also suggest that the engines were not thermally overloaded when operating on biodiesel although more fuel was input in order to keep the same power output from engines [44]. Another possible explanation of the lower value of exhaust temperature could be because WFOME has got lower heating value and higher cetane number than diesel fuel. Ignition delay occurred in fewer periods because of higher cetane number resulting in decrease in exhaust temperature. At the same time, due to the fact that the density and kinematic viscosity of biodiesel is higher than petroleum diesel fuel, the spray penetration for biodiesel at low engine speed may be long and this causes a poor atomization rate. Consequently, these factors reduced the exhaust gas temperature.

For various UCOME and their blends, some authors have reported higher exhaust temperatures at full loads with an increase in exhaust temperature with percentage of UCOME [21,31,35]. These may be due to more fuel being burnt at higher loads to meet the power requirement and higher oxygen content of the UCOME, which improves combustion and thus may increase the exhaust gas temperature. Another contributing factor to this increase may be the due to higher physical delay period in WCO biodiesel operation the combustion is delayed. As the combustion is delayed, injected WCO biodiesel fuel particles may not get enough time to burn completely, hence some fuel mixtures tend to burn during the later part of expansion, consequently afterburning occurs. The exhaust gas temperature is a convenient scale to study

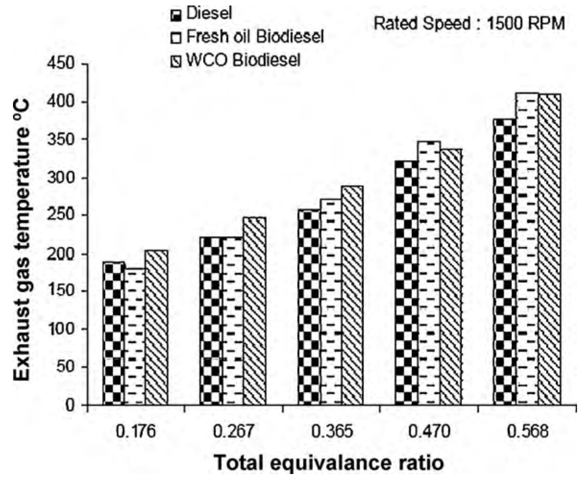


Fig. 2. Exhaust gas temperature versus total equivalence ratio.

the extent of afterburning. And it was observed that the exhaust gas temperature was reasonably higher for WCO biodiesel compared to baseline diesel as depicted in Fig. 2 [21]. Hence certain extent of afterburning can be expected during the WCO biodiesel operation.

3.1.2. Nitrogen oxides emissions

Most of the literature reviewed showed that there was a slight increase in NO*x* emissions when using UCOME biodiesel. However, some other works found that NO*x* increased only under certain operating conditions such as test conditions, load conditions, alcohol-base of ester (methyl, ethyl) and the effect of UCOME in the blends. While some works found reduction in NO*x* emissions when using UCOME and its blends, other works did not find any differences in the NO*x* emissions between UCOME and/or its blends and fossil diesel.

Various reasons have been given for the increase in NO*x* emissions when using biodiesel and/or its blends. NO*x* emission is primarily a function of pressure, temperature and total oxygen concentration inside the combustion chamber. One argument is that the increases in NO*x* emissions obtained are in proportion to the concentration in biodiesel [49]. It is has been argued that the increase in NO*x* emissions with increase in the percentage of UCOME in the blend may be associated with the increased oxygen content of UCOME. Invariably all biodiesel have some level of oxygen bound to its chemical structures. Hence, oxygen concentration in WCO biodiesel fuel might have influenced the NO*x* formation. Being an oxygenated fuel, UCOME also supplies oxygen in addition to air inducted into the combustion chamber and this may aid the formation of NO*x*. Another contributing factor may be the possibility of higher combustion temperatures arising from improved combustion as a larger part of the combustion of UCOME and its blends is completed before TDC due to lower ignition delay. Also, the enhanced fuel-air mixing at higher speed may result in higher NO*x* formation. According to Lapuerta et al. [41], increase in NO*x* emissions from biodiesel fuels can only be explained by the advance of injection start when compared to diesel fuel especially in the case of a pump-line nozzle injection system, where apart from being advanced as a function of the accelerator position, the injection is affected by the pressure transmission speed through the injection line. However, several publications have reported the influence of biodiesel characteristics. Graboski et al. [50] have shown that NO*x* emissions increase with decrease in mean carbon chain length and increase in unsaturation. Increase in NO*x* emissions with increase in iodine number has earlier been reported by Peterson et al. [51]. Graboski et al. [50] showed by a linear relationship with iodine

number as this accounts for the number of double bonds in ester molecule. According to the authors, iodine number is closely related to density, compressibility and cetane number. However, they suggested that the increase in NOx emissions was due to the effects on the injection or combustion timing rather than by molecular unsaturation. The US Environmental Protection Agency [52] and Wyatt et al. [53] have confirmed a direct relationship between NOx emissions and molecular unsaturation. Tat [30] also observed increased NOx emissions from soybean with respect to those measured from a more saturated waste oil biodiesel. A detailed observation of the results obtained by Lapuerta et al. [41] showed a slight decrease in NOx emissions from ethyl esters with respect to methyl esters due to the slight difference in oxygen content between them. Yoshimoto et al. [54] offered suggestions on ways of reducing NOx emissions in diesel engines fueled by biodiesel with used frying oil.

On the decrease in NOx emissions, in a direct injection naturally aspirated four-stroke diesel engine NOx emission is sensitive to oxygen content, adiabatic flame temperature and spray properties. It is well known that biodiesel fuel does not contain sulphur, aromatics and hence nitrogen content is very small. The spray characteristics depend on droplet size, droplet momentum and degree of mixing with air and penetration rate, radiant heat transfer rate and evaporation rate. A change in any of these properties may change the NOx production. Furthermore, fuel chemistry effects in the flame region could account for a change in NOx production. All these may bring about lower formation of NOx in biodiesel than petroleum diesel fuel.

3.1.3. Carbon monoxide emission

The general trend observed in most of the literature reviewed was a decrease in CO emissions when substituting diesel fuel with UCO biodiesel and/or its blends. Nevertheless, a few authors found no differences between diesel and biodiesel/biodiesel blends, and even noticeable increases when using biodiesel and/or its blends. However, the effect of biodiesel content in the fuel together with the load conditions has to be taken into consideration. Some of the studies reported a reduction in CO emissions when using pure biodiesel and an increase in CO emissions with blends. Load conditions have been proved to have a remarkable effect on CO emissions.

Another consideration which may be of importance is the effect of biodiesel characteristics. CO emissions have been known to decrease with increase in saturation level [52]. The same result has been reported by [29,30,50] when they tested conventional biodiesel fuels from neat vegetable oil and used cooking oils and compared the results with diesel fuel. Hamasaki et al. [27] studied the effect of biodiesel acidity and oxidation on CO emissions. They observed that CO emissions were increased as the acid value was increased. It was explained that this trend might have been due to a higher hydroperoxide concentration as the acid value was higher, since they participate in CHO, HCHO and CO formation reactions.

The reasons which have been given for the general decrease in CO emissions from biodiesel include the additional oxygen content in the fuel, which improves combustion in the cylinder. Biodiesel also has higher cetane number and is less compressible than diesel fuel. Increased cetane number of biodiesel fuel lowers the probability of forming fuel-rich zone and the advanced injection timing. All these bring about shorter ignition delay, longer combustion and increase in complete combustion reaction regions. If a fuel is less compressible, the injection starts earlier and causes longer combustion duration.

3.1.4. Un-burnt hydrocarbon emission

Un-burnt hydrocarbon emissions consist of fuel that is completely unburned or only partially burned. Most authors in the papers reviewed reported a sharp decrease in un-burnt hydrocarbon emission (see Fig. 3 [21]). However, Hamasaki et al. [27] observed increase in UBHC emissions when fuelling diesel engines with UCO biodiesel. Akko et al. [55] studied the influence of biodiesel content with load conditions by testing a heavy-duty engine on the ECE R49 test cycle with diesel fuel and three biodiesel fuels from rapeseed, soybean and used cooking. UBHC emissions were reduced when biodiesel fuels were used. Canakci and Van Gerpen [29] and Tat [30] obtained 50% UBHC reduction when using pure biodiesel regardless of the origin and concluded that biodiesel origin is not a factor affecting UBHC emissions. Lapuerta et al. [41] reported that ethyl esters from UCO showed lower UBHC emissions than methyl esters in medium conditions, and no clear trend in low load condition. This trend is in agreement with the observation made by Peterson and Reece [56] and could be explained by the lower heat of vaporization of ethyl esters.

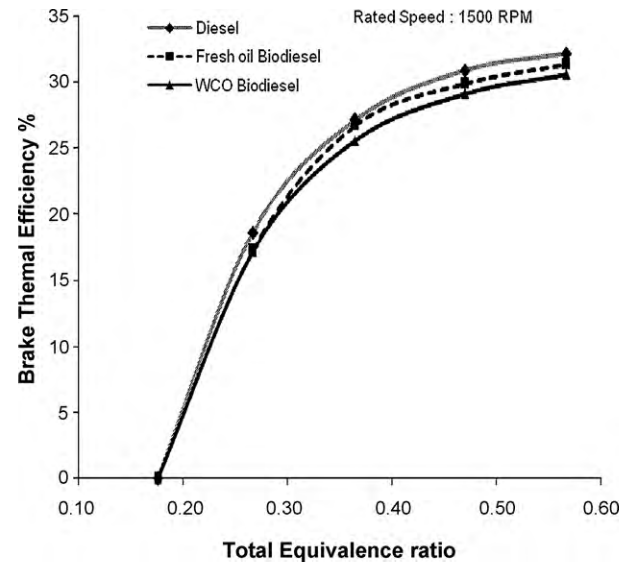


Fig. 3. Brake thermal efficiency versus total equivalence ratio.

The amount of UBHC in the exhaust depends on the engine's operating conditions, fuel properties, fuel-spray characteristics, and the interaction between fuel spray and air in the combustion chamber. Probably, the higher oxygen content of biodiesel in combustion region provides more complete combustion. This means that biodiesel in the fuel mixture increases the cetane number and oxygen content of the blend; this causes higher combustion efficiency and reduces the level of UBHC emissions. However, at high engine speeds, the UBHC emissions show similar behavior regardless of the fuel type due to higher injection pressure and better atomization ratio. The main reason for reduced UBHC emissions at high engine speed is increased atomization ratio. At the same time, high engine speeds cause the increased inlet air flow speed or turbulence. This enhances the effect of atomization of the fuel in the cylinder, makes the mixture more homogeneous, and reduces UBHC emission [47].

3.1.5. Particulate matter and smoke intensity

Although Lin et al. [38] reported an increase in particulate matter emissions when using UCO biodiesel, a noticeable decrease in PM emissions and smoke opacity with the biodiesel content was the observed trend in the literature reviewed. The effect of biodiesel on PM emissions is better studied in conjunction with other parameters such as load conditions, the quality of the diesel fuel used for blending and type of engine used. Most reports showed a larger decrease in PM emissions at high load operation conditions. This trend was attributed to the fact that particles are mainly formed

during diffusion combustion, and at high load most of the combustion process is diffusive. Also the higher oxygen content of ester fuel provided more oxygen for combustion and soot oxidation. Thus, the oxygen content of biodiesel is more effective in reducing PM emissions. Durbin and Norbeck [57] used a sharp increase in soluble organic fractions (SOF) at low load to explain the large decrease in PM emissions when biodiesel from yellow grease was used. Armas et al. [37] attributed the lower smoke opacity from their test to the higher viscosity and lower volatility of biodiesel which brought about difficulties in fuel atomization and evaporation in cold conditions of the start-up period.

On the effect of biodiesel characteristics, it is not clear from the literature reviewed whether or not PM emissions and smoke opacity depend on the biodiesel feedstock. Both Canakci and Van Gerpen [29] and Tat [30] tested two biodiesel fuels from used cooking oil and soybean oil in similar engines. Both biodiesel fuels provided reductions in PM emissions but there was no difference between them. If the effect of the alcohol used is analyzed [22], noticeable differences were observed between UCOME and UCOEE (used cooking oil ethyl ester) in the case of smoke opacity, as PM emissions are partially compensated by the adsorbed organic fraction (AOF), which is higher in case of UCOME. Since there are very slight differences in oxygen content between UCOME and UCOEE, it may be concluded that the main factor affecting PM formation and emission is the oxygen content in the fuel, which is almost constant for every biodiesel.

Smoke opacity is strongly dependent on the amount of air in the cylinder as well as on the amount of oxygen in the fuel. It is obvious that fuel composition affects the amount of smoke produced by an engine. Especially, the sulphur and oxygen contents of the fuel affect the smoke formation and oxidation, respectively [47].

4. Engine performance characteristics

Sudhir et al. [21] carried out engine performance test on a single-cylinder, four-stroke, naturally aspirated, direct injection, water-cooled diesel engine test rig. The test was conducted at various loads starting from no load condition to the rated full load using diesel, fresh oil biodiesel and WCO biodiesel. Results showed that the performance of the pure WCO biodiesel was only marginally poorer at part loads compared to diesel fuel performance. At higher loads the engine suffers from nearly 1–1.5% brake thermal efficiency loss. However, thermal performance of WCO biodiesel closely bears a resemblance to the performance of fresh oil biodiesel (Figs. 4 and 5 [21]).

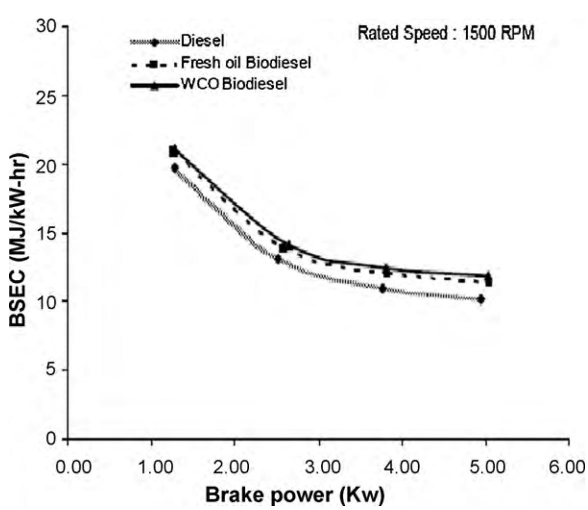


Fig. 4. BSEC versus brake power developed for the three test fuels.

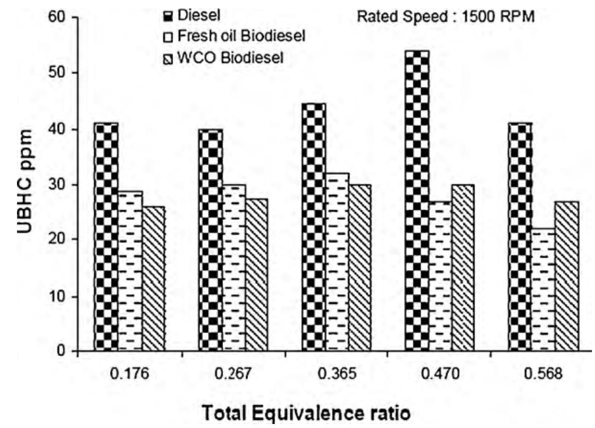


Fig. 5. UBHC emission versus total equivalence ratio.

Mittelbach et al. [25] tested methyl esters that were prepared using waste cooking oil in a Volkswagen Rabbit automobile powered by a 1.6-L four-cylinder, four-stroke diesel engine with direct injection. A mixture of the ester fuel/diesel fuel at ratio of 1:1 was chosen, and a total of 100 L of ester was consumed. Results showed that the consumption of fuel was almost the same as diesel fuel and no change in the operation of the engine was observed.

Three tests were conducted with different blending ratios of biodiesel and diesel on a Cumine LT10 engine test bed, Isuzu 5-tonne lorry and a Robin GS 3300RD diesel generator, respectively [26]. Results indicated that there was a slight increase in the rate of fuel consumption with increasing biodiesel percentage for both idle and loaded conditions. A 4% increase in fuel consumption was observed under loaded condition when diesel was totally replaced by biodiesel. Also, there was a slight increase in fuel consumption per kWh with increasing biodiesel percentage.

Hamaski et al. [27], on testing a single-cylinder engine at different loads and constant engine speed using three biodiesel fuels obtained from WCO but with different acid values, observed that the brake thermal efficiency was similar in all cases.

Similarly, Guo et al. [28] tested biodiesel produced from recycled oil in a 1998 FORD light goods van with a four-stroke, four-cylinder, water-cooled diesel engine. A linear decreasing trend of maximum engine power with biodiesel percentage was observed. However, the power variation was small for all biodiesel blending percentages tested.

The utilization of ethyl ester obtained from waste palm oil as fuel in diesel engines was investigated by Al-Widyan et al. [31]. The test was conducted in a single-cylinder direct injection engine by blending different proportions of the ester with diesel fuel. A comparison among the blends reveals that the 100% ester (100O) and the 75:25 ester/diesel blend (25D), in overall terms, performed the best. They resulted in the more steady performance over the speed range considered as indicated by the maximum brake power, essentially the lowest brake specific fuel consumption (BSFC), and highest thermal efficiency.

Canakci and Van Gerpen [29] compared waste oil and soybean oil biodiesel fuels in a 57 kW engine. The tests showed that there was about 2.5% increase in brake specific fuel consumption with 20% blends and 14% from those with pure biodiesel. The study also showed no variations in brake thermal efficiency when using different types of biodiesel fuels.

A test carried out by Dorado et al. [18] on exhaust emissions from a diesel engine fuelled with transesterified waste olive oil on DI Perkins diesel engine showed that there was a slight increase in BSFC (lower than 8.5%).

Ulusoy and Tekin [32] conducted engine tests of biodiesel from used frying oil. Comparative measurements with No. 2 diesel fuel

were made on engine power characteristics. Biodiesel, when compared to No. 2 diesel fuel, showed reduction in wheel force over 3.35% and also reduced the wheel power by over 2.03%. In the acceleration tests, 40–100 km/h and 60–100 km/h acceleration periods were measured and a reduction of 7.32% and 8.78% were observed, respectively. When the amounts of fuel consumption were compared, it was observed that biodiesel consumption was 2.43% less than that of No. 2 diesel fuel.

Results of emission and performance characteristics of a 2-L Toyota diesel van operating on WCO biodiesel and diesel fuel indicated a difference of approximately 9% in brake power between the two fuels with biodiesel having lower brake power [33].

Usta et al. [35] produced biodiesel from a hazelnut soapstock/ waste sunflower oil and examined the effects of the biodiesel addition to No. 2 diesel on the performance of a four-cycle, four-cylinder, turbocharged indirect injection diesel engine at both full and partial loads. The power variation with biodiesel contents in the blend was also studied and it was observed that the power initially increases with the addition of biodiesel, reaches a maximum, and then decreases with further increase in biodiesel content. Results indicated that biodiesel blends (5%, 10%, 15%, 17.5% and 25% biodiesel addition) produced a slightly higher torque and power at both loads. It was found that 17.5% biodiesel addition gave maximum power and thermal efficiency.

Özkan et al. [20] tested WCO biodiesel in a single-cylinder DI diesel engine. Compared with diesel, a 25% power loss occurred. While the maximum torque of 21.0 Nm was observed for diesel at 1500 rpm, a maximum of 18.4 Nm at 2250 rpm was obtained for biodiesel. Also, the specific fuel consumption of diesel was 11.5% lower than that of biodiesel.

The engine performance test and road test performance results of UCO-originated biodiesel were evaluated in a Renault Mégane automobile with a four-stroke, four-cylinder, F9Q732 and 75 kW Renault Mégane diesel engine in winter conditions for 7500 km road tests and the measured results were compared to No. 2 diesel fuel [34]. The results indicated that the torque and brake power output obtained using the biodiesel were 3–5% less than those of No. 2 diesel fuel while the fuel consumptions are very similar.

The investigation of engine performance of biodiesel from UCO in electric generators conducted by Cetinkaya and Karaosmanoğlu [36], indicated that compared to No. 2 diesel fuel and 100% biodiesel (B100), B20 showed improved results, in regard to engine performance as higher power generation and lower BSFC were recorded.

In a combined test bench/on-road program for biodiesel promotion carried out in Australia with waste oil biodiesel, a loss of rated power of 17% was found in the bench, this loss being slightly higher than expected. The low methyl ester content (below 90% in average) or the high acid value (0.9 mg KOH/g) was thought to have led to a lower than usual heating value. However, drivers declared not noticing any power loss on the road, probably as a consequence of the infrequent demand for full-load power [58].

Murillo et al. [59] tested diesel fuel and biodiesel from used cooking oil in a marine outboard three-cylinder naturally aspirated engine. At full load, the biodiesel resulted in a power loss of 7.14% as compared with diesel fuel, very close to the difference in heating values. Some results show 1.502% reductions in rated power when using 20% blends and 8% reductions when using pure biodiesel.

The engine test of biodiesel produced from waste cooking oil via alkali catalyst has been conducted on a turbocharged YC6M220G heavy-duty diesel engine by Meng et al. [40]. The fuel consumption was measured under two speeds, 1300 and 2200 rpm, respectively. For all the fuels tested, BSFC decreased with increase in load. It was observed that in general, the reference fuel B0 resulted in smaller fuel consumption per unit energy output compared to all other blends (B'20 refined biodiesel, B20 and B50). However, considering the fuel consumption at 1300 rpm, the minimal fuel consumption for B0, B'20, B20 and B50 was 203.4, 205.4, 210.7 and 222.8 g/kWh, respectively, with the most economical power 122.9, 121.9, 119.5 and 116.6 kW, which showed that there were little differences in engine performance of the fuel blends.

Utlu and Koçak [39] investigated the effect of biodiesel fuel obtained from waste frying oil on a turbocharged, four-cylinder, direct injection diesel engine performance. Gathered results were compared with No. 2 diesel fuel. Maximum torque obtained at 2000 rpm was 220 Nm for diesel fuel and 216.8 rpm for WFOME. Average decrease of torque values was 4.3% for WFOME. Although the maximum power measured at 4000 rpm was 72.4 kW for diesel fuel and 72 kW for WFOME, the WFOME power value was lower at an average of 4.5%. For both fuels, minimum BSFC obtained at 1750 rpm was 229.59 g/kWh for diesel and 258.66 g/ kWh for WFOME while the average BSFC for usage of WFOME was higher than diesel by 14.34%.

Lapuerta et al. [22] reported the result of testing WCO biodiesel in a DI diesel commercial engine either pure or blends with diesel fuel. From the results, it was observed that as the biodiesel concentration in the blend was increased, the BSFC increased. The efficiency of the engine remained unchanged at every tested operation mode. In investigating the effect of the alcohol type used in the production of WCO biodiesel on diesel performance, Lapuerta et al. [41] obtained similar results: the use of pure biodiesel fuels and their blends, compared to diesel resulted in a slight increase in fuel consumption while the brake thermal efficiencies were similar.

The performance characteristics of UCOME and its blends with diesel fuel were analyzed in a direct injection compression ignition engine by Rao et al. [23]. The results showed that while the BSFC is slightly higher than that of diesel for UCOME and its blends, the brake thermal efficiency for UCOME and its blends was lower than that of diesel fuel by 2.5%. The brake thermal efficiency of blends of UCOME lies between those of diesel and UCOME at all loads.

Waste palm oil biodiesel produced by microwave-assisted irradiation process was tested in a 100 kW diesel generator as a neat fuel (B100) and 50% blend with No. 2 diesel fuel (B50) by Lertsathapornsuk et al. [42]. Engine loads were varied from 0 to 75 kW (at 25 kW intervals). The specific fuel consumption of the diesel generator powered by B100 (without any engine modification) increased by $12.73 \pm 0.03\%$ while that of B50 showed an increase of $5.60 \pm 0.02\%$ with respect to diesel. The engine efficiencies of the generator powered by biodiesel were similar to those powered by diesel at all levels of electrical loads. The highest engine efficiency was observed at the electrical load of 50 kW. The average engine efficiencies of the engine powered by B100 and B50, at 50 kW load, were slightly lower than diesel by $0.26 \pm 0.03\%$ and $0.24 \pm 0.02\%$, respectively. On the other hand, at 75 kW electrical loads, engine efficiencies of B50 and B100 were higher than that of diesel.

Similarly, the performance of microwave-enhanced WCO biodiesel was tested by Reefat et al. [43] in a Perkins four-cylinder, four-stroke cycle diesel engine. The results of the power tests of the biodiesel were similar to petroleum diesel fuel performance values. However, a slight increase in BSFC (lower than 8%) was detected with biodiesel.

Ghobadian et al. [46] studied the diesel engine performance using WCO biodiesel with an artificial neural network. The experimental results revealed that blends of WVOME with diesel fuel provide better engine performance. It was observed that the ANN model can predict the engine performance quite well with correlation coefficient $R = 0.9487$ and 0.999 for the engine torque and SFC, respectively.

Canakci et al. [47] investigated, using neural network the performance of a diesel engine fueled with waste frying palm oil biodiesel. It was observed that the brake specific fuel consumption

increased with the increase of biodiesel percentage in the fuel blend while the predicted values for the brake torques and brake thermal efficiency decrease with the increasing amount of biodiesel in the fuel blend.

5. Analysis of engine performance characteristics

5.1.1. Brake effective power

Most of the literature reviewed reported a slight reduction in power especially with increase of biodiesel in the blends. Some have used the reduced heat content of biodiesel and/or its blend to explain this power loss. However, it may be argued that the higher brake specific fuel consumption (BSFC) of biodiesel and/or its blends will compensate this and maintain the same power. Other authors have justified the loss of power as a result of fuel flow problems and difficulties in the fuel atomization.

Surprisingly, some publications have reported increases in effective power when using biodiesel which they attribute to higher cetane number, higher density and viscosity, and improved combustion. It is also possible that at low engine speed, there is enough time for most fuel-rich zones in combustion chamber to burn leading to better combustion of biodiesel.

Finally, one of the papers reported no significant differences on the brake effective power with biodiesel and/or its blends and diesel fuels.

5.1.2. Brake specific fuel consumption

Brake specific fuel consumption is one of the important parameters of an engine and is defined as the consumption per unit power in a unit of time. Most of the literature reviewed showed that the brake specific fuel consumption is higher for UCOME and its blends than for diesel. Also, increasing the percentage of UCOME in the blend increases the brake specific fuel consumption. Generally, this increase in specific fuel consumption has been attributed to the lower calorific value of biodiesel, and possibly higher density compared to diesel fuel. It has also been observed that the atomization ratio and injection pressure have some effects on the brake specific fuel consumption [46]. Some methods of reducing BSFC have been suggested by Yoshimoto et al. [54].

5.1.3. Brake thermal efficiency

Biodiesel has lower calorific value on weight basis because of presence of substantial amount of oxygen in the fuel but at the same time has a higher specific gravity as compared to conventional diesel fuel. The overall impact has been put by Agarwal [60] to be approximately 5% lower energy content per unit volume. However, the comparison of fuels with different calorific values and densities based on brake specific fuel consumption could be misleading. If different fuels are compared, it should be noted that their calorific values decrease with the increase of biodiesel in the blend and also that the calorific value is lower than petroleum diesel, for that reason, brake thermal efficiency may be used instead of brake specific fuel consumption [59].

There have been different reports when the brake thermal efficiency of UCOME and its blends are compared with diesel fuel. Some researchers have reported high brake thermal efficiency for engines fueled with UCOME than that of diesel, while its blends are observed to have lower efficiency than diesel [59]. A possible explanation for this increase was attributed to the atomization of the blends during injection and/or with the stability of the mixtures of fuels during storage, pumping and injection. Another possible reason may be the reduction in friction loss associated with higher lubricity. However, while some reports showed lower thermal efficiency for UCOME and its blends compared to diesel fuel, other authors find similar thermal efficiency to diesel fuel when using biodiesel and/or its blends. A possible reason for poor thermal performance of the WCO biodiesel compared to base line diesel operation may be attributed to its higher viscosity and lower cetane index. However, Sudhir et al. [21] observed that the thermal performance of WCO biodiesel almost resembles to fresh oil biodiesel.

6. Conclusion

It has been found that UCO biodiesels are usually the same as biodiesel from fresh vegetable oil. So the influence of UCO biodiesel (like biodiesel from neat vegetable oil) on engine performance and combustion characteristics is probably more closely related to the oxygenated nature of biodiesel (which is almost constant for every biodiesel), and also to its higher viscosity and lower calorific value, which have a major bearing on spray formation and initial combustion. The summary of the present literature review is as follows:

The ignition delay of UCO biodiesel decreases with increase in percentage of UCO in the blend and is less when compared to that of petroleum diesel. The peak pressure of UCO biodiesel and its blends is higher than that of diesel fuel. The maximum rate of pressure rise and maximum heat release for UCO biodiesel and diesel are similar. With increase in percentage of UCO biodiesel in the blend, these parameters decrease. Higher exhaust gas temperature of UCO biodiesel which increases with percentage UCO in the blend. Increased oxygen content which improves combustion is a reason given for this.

A relatively high disparity of results has been found regarding the emissions characteristics of used cooking oil biodiesel and/or its blends. Although, a dominant trend has been found in most cases, there have always been opposing trends proposed elsewhere by contrast. The precise features of the engines tested and their operating conditions, the different biodiesel fuels used, their characteristics, qualities and blends, measurement techniques and procedures, and instrumentations have a strong influence on the impact of UCO biodiesel. Hence, each study was specific.

Most of the reports recorded slight increases in NO_x when compared to diesel at rated load. The reasons most frequently given include higher oxygen content of biodiesel and its blends and advanced injection process with biodiesel. CO and UBHC emissions were found to significantly decrease with biodiesel and its blends due to a more complete combustion caused by higher oxygen content. Origin of biodiesel is not a factor in UBHC emissions although UCOME showed lower emission than UCOEE. It is also reported that there is a sharp reduction in particulate matter and smoke intensity in UCO biodiesel and its blends. The reduction is mainly caused by reduced soot formation and enhanced soot oxidation due to increased oxygen content. There was no difference in PM emissions between UCO and fresh vegetable oil biodiesel. There was a noticeable difference between UCOME and UCOEE in smoke opacity but not in PM.

The effective power depends on the load conditions showing a decrease at full-load conditions and no differences at partial load conditions. An increase in brake specific consumption has been found when using UCO biodiesel in most of the papers reviewed. BSFC increases with increase in percentage of UCO biodiesel in the blend and is due to the lower heating value of UCO biodiesel and its blends. While some authors find similar brake thermal efficiency to diesel fuel when using UCO biodiesel or its blends others reported decrease with increase in percentage of UCO in the fuel.

The findings from this review indicate that biodiesel derived from used cooking oil is a cheap green liquid fuel available because of the primary ingredient being a post-consumer waste product.

UCO biodiesel when used in diesel engines has shown an impressive engine performance, combustion and emission characteristics same as biodiesel from fresh vegetable oil which has been widely acknowledged as an alternative to petroleum diesel.

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